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*077863*

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**SAFETY REVIEW PACKAGE  
FOR UNIVERSITY OF CENTRAL FLORIDA  
FLAT-PLATE HEAT PIPE EXPERIMENT**

## **ABSTRACT**

A flat-plate heat pipe (FPHP) experiment has been set up for micro-gravity tests on a NASA supplied aircraft. This report presents an analysis on various components of the experimental setup to certify that it will satisfy the flight safety and operation requirements.

## INTRODUCTION

One of the most important elements affecting the reliability of electronic chips is the junction temperature. In order to work safely and reliably it is essential for the electronic chips to be cooled efficiently. In most cases, depending on the application, air-cooled finned exchangers or forced convective liquid-cooling system are used. These systems can be bulky because they do require support facilities such as pumps, filters, heat exchangers and coolant reservoirs. For spacecraft and certain ground based portable applications, the size and weight of the cooling systems are key features to be minimized. For spacecraft applications, because of the absence of convective cooling, heat dissipation is ultimately by radiation. Hence, for optimum performance of the radiator the temperature of the whole radiator surface should be as high as possible in order to reduce the size and weight of the radiator. These two requirements, namely, the temperature of the electronic chips being below a certain limit and the temperature on the radiator surface being maximized, together with the need to minimize the size and the weight of the systems, make the design window especially small for the spacecraft electronic cooling.

At the University of Kentucky a simple design modification of a heat pipe system was designed and tested, (see THEORY section). This Flat-Plate Heat Pipe (FPHP) concept allows the in-situ cooling of high-power electronics and the dissipation of the heat directly from the same FPHP envelope. Hence, the system is not only independent but also passive. The operation of a FPHP has been characterized under the influence of gravity. Two sets of tests were performed. One with the evaporator on the top and the condenser below, i.e., the gravity was in the negative direction to condensate flow. The second case was with the condenser on the top and the evaporator below, i.e., with gravity assisting condensate flow.

## TEST OBJECTIVE

The objective of the proposed in-flight micro-gravity experiments is to characterize the FPHP with no gravity assist, i.e., fluid pumping action is purely due to the capillarity in the wick structure. Because this study is acceleration-direction sensitive, the FPHP has been mounted on a gyroscope style gimbal to allow the plane of the FPHP to be always orthogonal to the direction of the resultant acceleration. Initial ground based experiments will be run to determine the capability of the gimbal mechanism to stabilize rapidly and to fine tune its operation. This is necessary as the anticipated period of micro-gravity in flight is about 20 seconds, a very short time. Hence, the FPHP must be aligned swiftly so as to get as much time as possible in a stable micro-gravity orientation. Then flight tests will be run for different heat flux rates to collect sufficient data to characterize the FPHP.

## THEORY

### Cylindrical Heat Pipe

The heat pipe, see figure 1, is a heat transfer device in which heat is absorbed at the evaporator interface through evaporation of a working liquid and then rejected at the condenser interface by condensation of the vapor. The vapor is transported from the evaporator to the condenser by the pressure gradient created by the generation of vapor at the evaporator and condensation at the condenser. The condensate is then pumped back to the evaporator by capillary forces in a wick structure or through body forces. Because only a pure liquid and vapor are present, the working fluid remains at saturation conditions, (assuming the system is above freezing and below the critical temperature). The heat pipe takes advantage of the constant temperature nature of the phase-change process to provide the maximum temperature (boiling point) for heat dissipation. At the same time because of the low thermal resistance it can transport heat over large distances by incurring very small temperature drops.

Figure 1 illustrates the operation of the cylindrical heat pipe. It consists of three distinct regions, namely, the evaporator, the adiabatic section and the condenser. Heat added to the evaporator region causes the working liquid soaked in the wick to evaporate or boil off. The higher temperature and the pressures in this region cause the vapor to flow towards the cooler regions of the condenser. Here the vapor rejects its latent heat of vaporization and condenses back to a liquid. The capillary forces within the wick structure soak up the condensate and pump it back towards the evaporator. In cases where gravitational or other bulk forces (e.g. centrifugal, electromagnetic) exist a wick may be dispensed with.

### Flat-Plate Heat Pipe

The flat-plate heat pipe (FPHP) is a geometrical modification of a cylindrical heat pipe, see figure 2. It takes the shape of a thin rectangular box. One face-plate is the evaporator, and the opposite face-plate serves as the condenser. The FPHPs are characterized by a very high effective conductance in the thermal spreading over the whole system and have been proven to be highly geometrically adaptable for electronic cooling in the space environment. The feasibility of using FPHP for electronic cooling in the space environment has been investigated by some researchers using different wicking structures, grooved surfaces, and working liquids. The major deficiency in the designs occurred for localized, concentrated heat loads, which precipitated dry out conditions in the evaporator section in the immediate vicinity of the heat load. Such a limitation to heat transport was a result of insufficient liquid return to the evaporator. An analysis of the flat plate heat pipe design indicated that the liquid had to be pumped through an extended circuitous path from the condenser to the evaporator, resulting in inadequate capillary pumping.

In order to circumvent the problem of insufficient pumping the FPHP design was modified to include inter-feeders. Figure 2 shows the newly developed flat plate heat pipe, into which the column-wick elements, or interfeeders, are introduced between the condenser and the evaporator. Such interfeeders provide a shorter path for the working

liquid to flow from the condenser back to the evaporator, and enforce and optimize flow of working liquid to regions of higher heat input. Also, to eliminate the contact resistance and the wall resistance, the heat generating electronic devices are mounted inside the evaporator plate. The device surfaces are covered with a liquid-soaked wick material. This essentially eliminates the temperature difference between the devices and working liquid, thereby resulting in the highest possible temperature at which heat is rejected by radiation and/or convection at the condenser plate. The FPHP with this structure is specially suitable to the space environment and some ground based portable application.

### Heat Transport Limitations

Given a particular coolant and capillary structure in a FPHP, an important specification sought is the maximum heat flux capability. During steady-state operation of a heat pipe, several important mechanisms exist that limit the maximum amount of heat transferred. Among these are the capillary wicking limit, the boiling limit, entrainment limit and sonic limit. The capillary wicking limit deals with the pressure drop occurring in the liquid and vapor phases, respectively. The sonic limit results from the occurrence of choked flow in the vapor passage, while the entrainment limit is due to the high liquid-vapor shear forces developed when the vapor passes in counter-flow over the liquid-saturated wick. The boiling limit is reached when the heat flux applied in the evaporator portion is high enough that nucleate boiling occurs in the evaporator wick, creating vapor bubbles that partially block the return of coolant liquid.

For moderate temperature heat pipes, the least significant of these limits are the sonic and entrainment limits. FPHPs have been studied with the capillary forces in the wick being augmented or diminished by the action of gravity under normal gravity situations. *The effect of no gravity assist has not been determined yet.* The heat transfer capability is also dominated by the boiling limit. This limit is referred to as the boiling critical heat flux (CHF) which is affected by the geometrical and physical conditions at the heated surface, the wicking materials, the orientation of gravity (nucleating bubbles have a buoyancy force imposed on them in a gravitational field), as well as the thermophysical properties of the working fluids.

### TEST EQUIPMENT DESCRIPTION

- A test rack supplied by NASA has been instrumented with:
- a cylindrical sealed FPHP
  - a brace and gimbal mechanism
  - a pc-based data acquisition
  - a power supply
  - wiring harness
  - wooden shelf

### **Cylindrical Sealed FPHP**

The FPHP is basically a hermetically sealed flat profile cylinder (or other geometry) with end caps. Inside is located a wick structure which assists in the pumping of the liquid from the evaporator (one of the end caps) to the condenser (the second endcap). The FPHP is characterized by a very high thermal conductance, having the capability to spread heat and equilibrate temperatures over large areas. The FPHP developed at the University of Kentucky incorporates interfeeders or column-like wick elements to provide shorter paths for the liquid return from the condenser to the evaporator, see figure 2. The wick is held firmly against the evaporator surface using springs. A thin film heater is attached to the evaporator face. The entire assembly is hermetically sealed with no external piping except for two wires to supply power to the evaporator side heater and thermocouple leads.

### **Brace and Gimbal Mechanism**

Figure 3 illustrates a schematic of the experimental setup. The FPHP is held in a brace which is further suspended in a gimbal mechanism, (see figure 4 for schematic), allowing two axis of rotation. The gimbal mechanism is further suspended in a double H-aluminum frame bolted to the test rack. From symmetry considerations the frame can be sectioned into four parts each being a mirror of the other. Figure 5 shows the stress analysis when the entire gimbal mechanism plus the FPHP is suspended from the aluminum frame and is subjected to a 7-g acceleration. It is noted that the maximum stress of 2968 psi occurs at the junction of the bearing. This stress is below the tensile stress limit of aluminum T6061 (5 to 21 kpsi) [1].

Figure 6 illustrates a quarter symmetry section of the outer arm of the gimbal, (see figure 4), with the respective load configurations. The gimbal members are made of steel. The symmetry is the same for the two rotating arms that make up the gimbal. On applying 7-g loads to both the outer and inner gyro arms and doing a stress analysis it is noted from figures 7 and 8 that the maximum stress induced in the arms is less than the maximum stress in steel ( $5.2 \times 10^8$  Pa) [1].

### **Coolant/Working Fluid**

When electronic circuits are in direct contact with the working liquid, both working fluid and wicking materials covering the chip surfaces must be dielectric. For this FPHP set of experiments, Fluorinert<sup>TM</sup> Electronic liquid FC-72 (boiling point 56 °C at 1 atm) has been selected as the working fluid, (see MSDS in Appendix A). The FPHP is charged with approximately 10 cc of the fluid. The FPHP is a closed system and no leaks are expected. Fluorinert<sup>TM</sup> electronic liquids are members of a family of completely fluorinated organic compounds, characterized by a variety of unique properties. These liquids are clear, colorless, odorless, thermally stable, non-flammable, essentially inert and non-solvent. These properties make the liquids compatible with materials of construction used by the electronic industry. The electrical insulating and dielectric characteristics of these fluids are excellent. Liquid phase dielectric strength is about 177 kV/cm. The vapors are also excellent insulators.

### **PC-Based Data Acquisition (DAC)**

A PC-based data acquisition system is part of the experimental setup, (see figure 3). Appendix B gives the summary of the stress calculations on the setup. As is noted, the induced stresses in the angle aluminum and steel bolts is far lower than the yield stress [1]. The internal components of the DAC are further braced wherever possible to handle the occurrence of a seven 'g' accelerations. The power input to the heater, the output of the thermocouples, and the aircraft accelerometer outputs will be connected to the data acquisition, (see figure 9 and 10 for circuits). During the period of micro-gravity conditions data will be acquired at a rate of 200 readings per second. This data will be analyzed on return to the laboratory. Information on the conditions within the FPHP will be continuously monitored and displayed by the computer during flight.

### **Power Supply**

A dc power supply is firmly affixed (bolted) to the test rack via an aluminum frame. Appendix C gives the summary of the stress calculations on the setup. As is noted, the induced shear stress is far lower than the yield stress of the bolt material [1]. The internal components of the power supply are further braced wherever possible to handle the occurrence of a seven 'g' accelerations. The aircraft 115 VAC system will be used as the input power to this power supply.

### **Wiring Harness**

The various power and data wires are clamped securely to the test rack to prevent any chance of loose connections developing due to vibrations or motion of the various components during the experiment.

### **Wooden Shelf**

The data acquisition, power supply and PC-notebook are bolted via the clamps and braces to a wooden shelf supported on two inch angle aluminum. Appendix D gives the summary of the stress calculations on the setup. As is noted, the induced shear stress is far lower than the safe yield stress of the wooden shelf [1].

### **Parabola Requirements, Number, and Sequencing**

A total of three flights are anticipated for three different heat pipe wick configurations. Each flight will include a total of eight parabolas. The data from each parabola will be recorded over a period of about 5 minutes. This will include approximately 3 minutes prior to zero-G, 20 seconds of zero-G, and approximately 2 minutes after zero-G. The 3 minutes prior is necessary to stabilize the heat pipe operation to the predetermined conditions. The last two parabolas will be run to determine the effect of higher G (1.5 G to 2.5 G). The seventh parabola will be run with the G in the direction of liquid flow in the FPHP wick and the eight parabola with the FPHP in the counterflow G direction.



## Test Procedure

### Ground Assembly and Preparation

The experimental setup will be provided completely assembled and flight ready. Three flights have been requested to test three different FPHP wick configurations. The FPHP is designed to be modular to facilitate ease of changing even during flight. Hence, if conditions are such that steady state in the operation is reached earlier, either more parabolas will be requested or the FPHP will be switched and tests continued on the new specimen. On loading the experimental setup onto the aircraft, the main power cord must be connected to the aircraft 115 VAC bus. Also, the aircraft accelerometer outputs must be connected to the data acquisition panel.

### Ground Testing

- Power up the experimental setup using the main switch on plug strip.
- At the DOS prompt (C:) type *GO*.
- Set the variable voltage supply to a predetermined value (will be given).
- The data acquisition will begin monitoring and displaying all the relevant parameters.
- The heat flux and temperatures displayed must concur with the supplied data in order to certify that the FPHP is functioning OK.
- If all is well, switch off the variable power supply, and let the FPHP cool down.
- Exit the data acquisition program by typing *ALT-E*.
- Switch of the main switch at the plug strip.

### During Flight - Testing

- Once the aircraft is airborne and at cruise altitude.
- Power up the experimental setup using the main switch on plug strip.
- At the DOS prompt (C:) type *GO*.
- Set the variable voltage supply to a predetermined value (will be given).
- The data acquisition will be monitoring and displaying all the relevant parameters.
- When the heat flux and temperatures displayed stabilize (do not change over 5% in one minute), then type *ALT-D*. The data acquisition begins to store data on the disk. Within the next 20 seconds take the aircraft into the parabola. Two minutes after the parabola is complete, type *ALT-S* (stop storing data). The information provided from each parabola will give the initial steady state, the zero-G data, and the time needed to stabilize after the 1-G to zero-G to 1-G transients.
- Repeat each setting of the voltage input twice to determine repeatability.
- On completion of the tests, switch off the variable power supply, and let the FPHP cool down.
- Exit the data acquisition program by typing *ALT-E*.
- Switch off the main switch at the plug strip.

## **TEST SUPPORT REQUIREMENTS, GROUND AND FLIGHT**

### **Ground Support**

Access to a 115 VAC, 60 Hz supply.

### **Flight Support**

The experiment requires access to the aircraft 115 VAC, 60 Hz power supply and the three axis accelerometer signal.

## **TEST OPERATING LIMITS OR RESTRICTIONS**

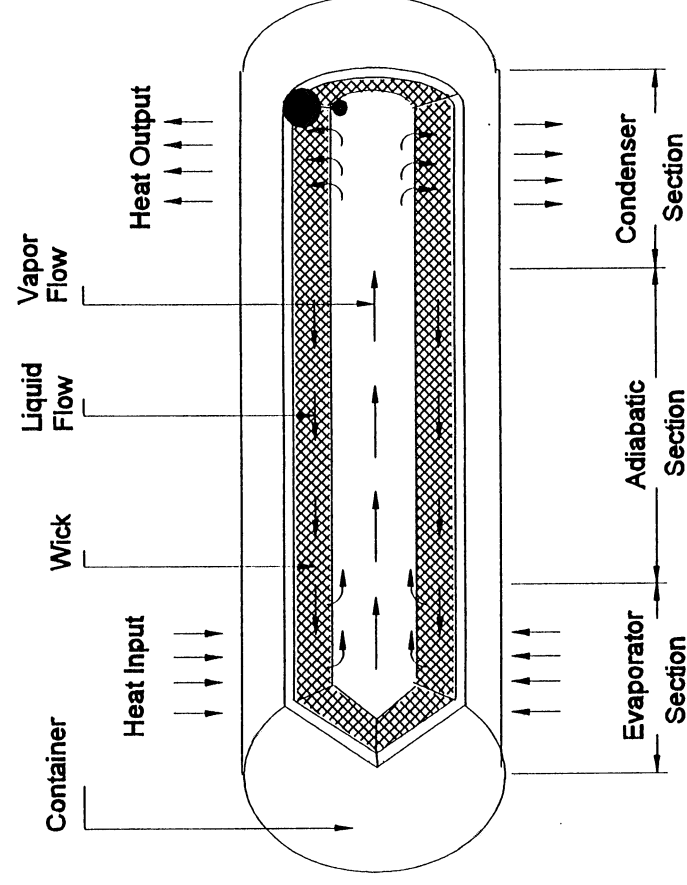
For these tests there are no test operating limits or restrictions identified at this time.

### **References**

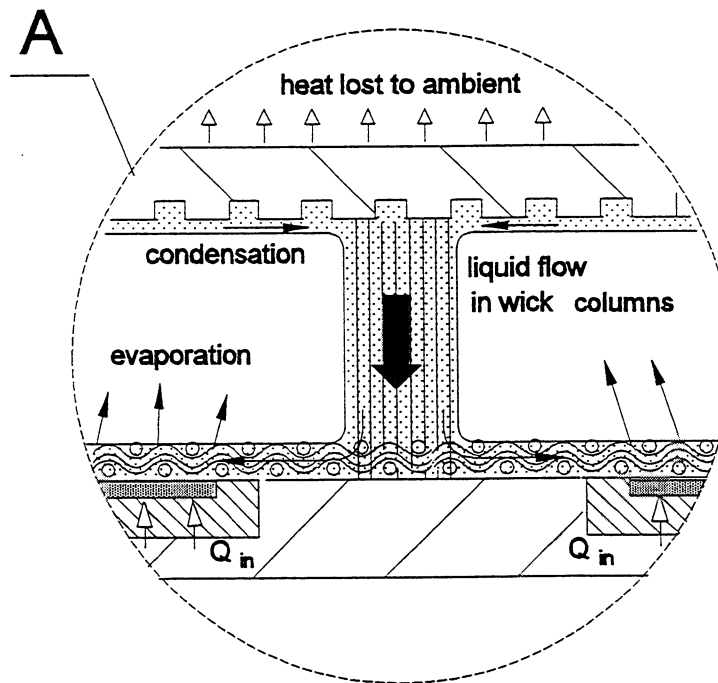
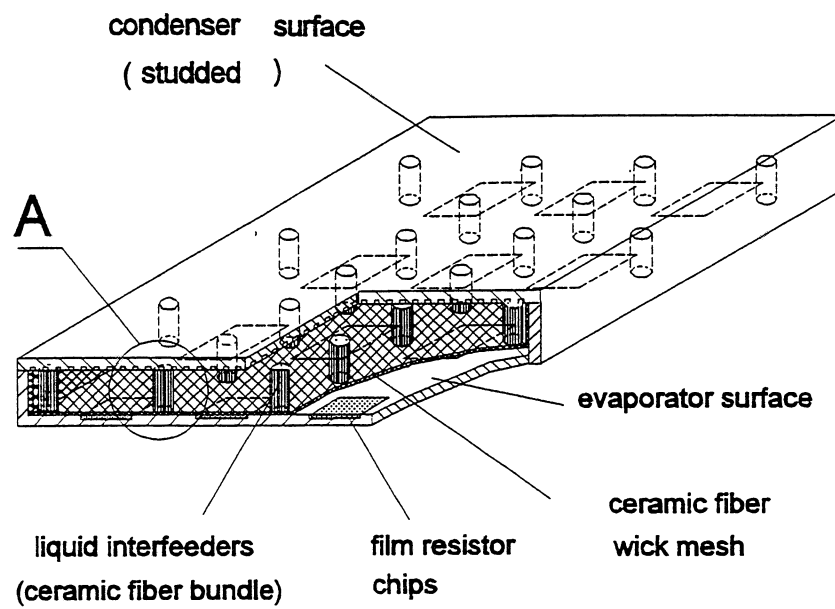
Marks Standard Handbook for Mechanical Engineers, Ninth edition.

## **PROPOSED MANIFEST FOR EACH FLIGHT**

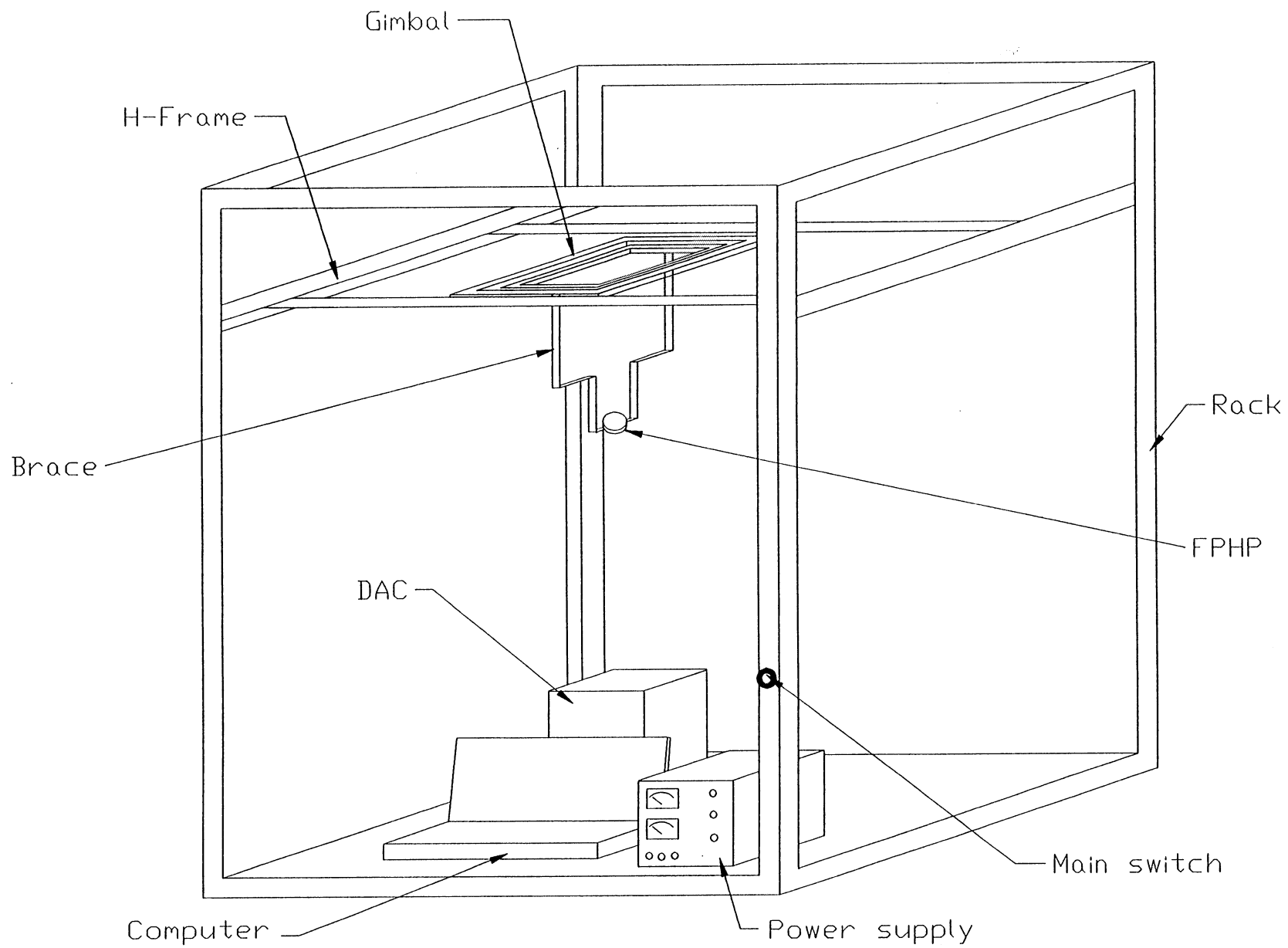
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University of Central Florida  
Orlando, FL 32816-2450  
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chowlc@pegasus.cc.ucf.edu



**Figure 1** Components and principle of operation of a cylindrical heat pipe



**Figure 2** Configuration of a flat plate heat pipe.



**Figure 3: Experimental Setup**

UK		
SETUP		
1:1	12-Dec-95	
SCALE	DATE	DRAWING NO.

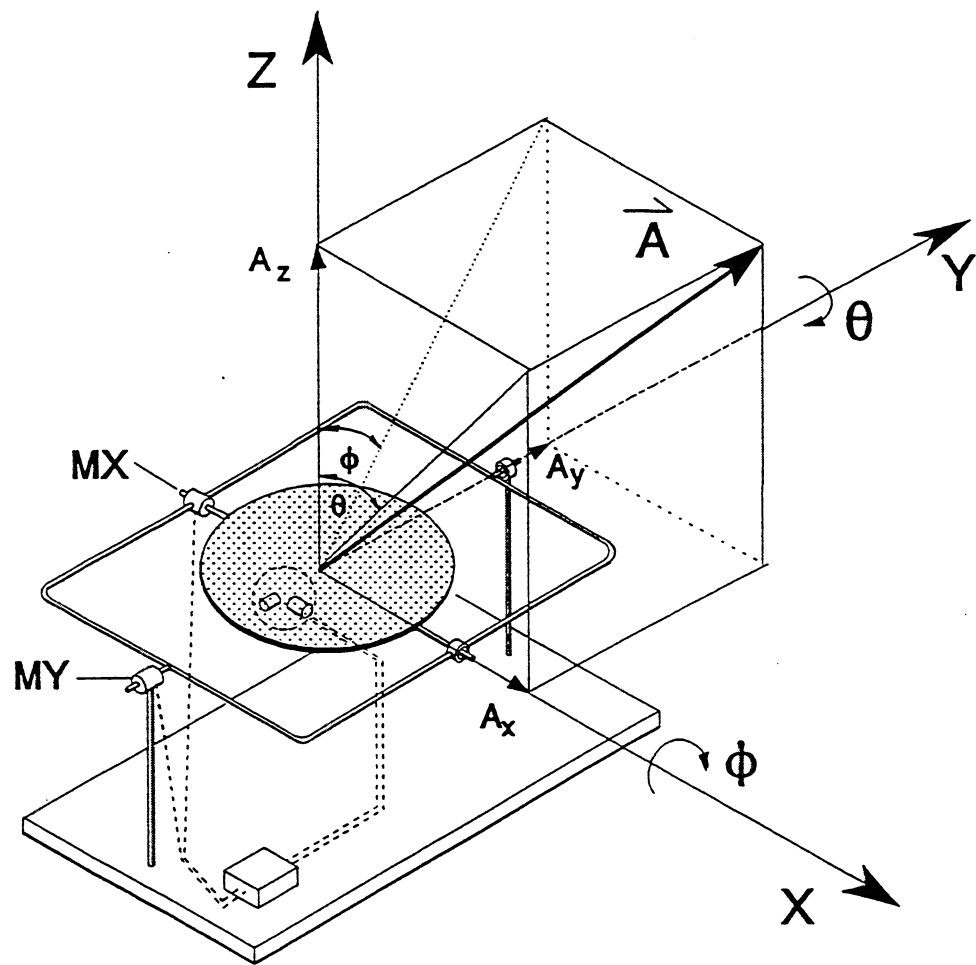
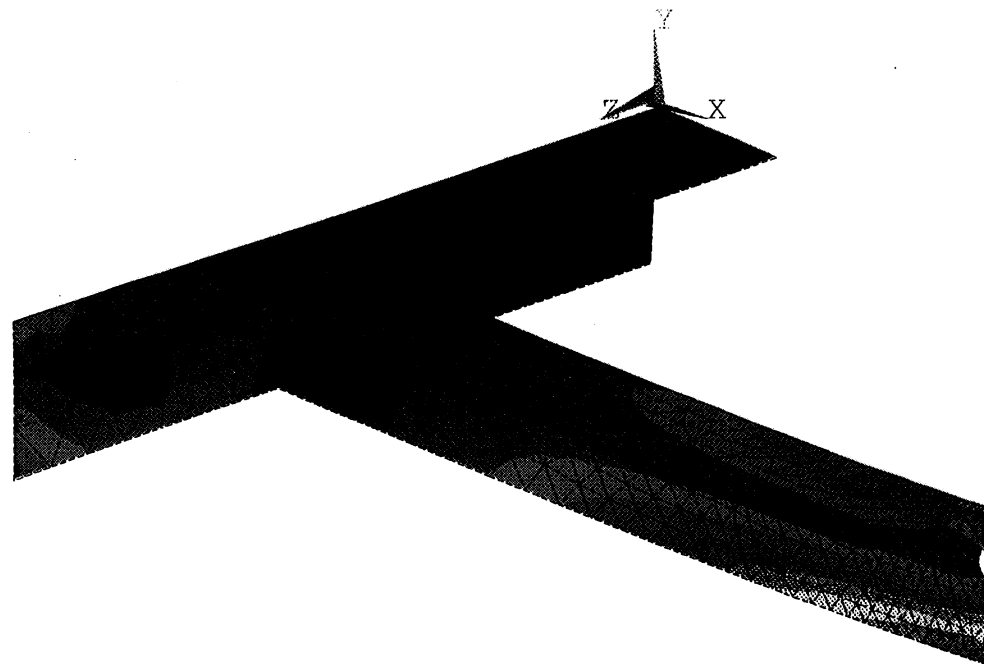


Figure 4: Gimbal mechanism



ANSYS 5.1  
MAY 28 1995  
01:12:42  
PLOT NO. 1  
NODAL SOLUTION  
STEP=1  
SUB =1  
TIME=1  
SEQV (AVG)  
TOP  
DMX =0.01101  
SMN =20.432  
SMX =2968  
SMXB=3655  
20.432  
347.968  
675.504  
1003  
1331  
1658  
1986  
2313  
2641  
2968

Figure 5: H-Frame  
Stress Analysis

ANSYS 5.1  
MAY 27 1995  
21:27:33  
PLOT NO. 1  
ELEMENTS  
TYPE NUM  
U  
F  
NFOR  
RFOR  
ACEL

XV =1  
YV =1  
ZV =-1  
DIST=0.095672  
XF =0.054  
YF =0.009  
ZF =-0.06  
CENTROID HIDDEN

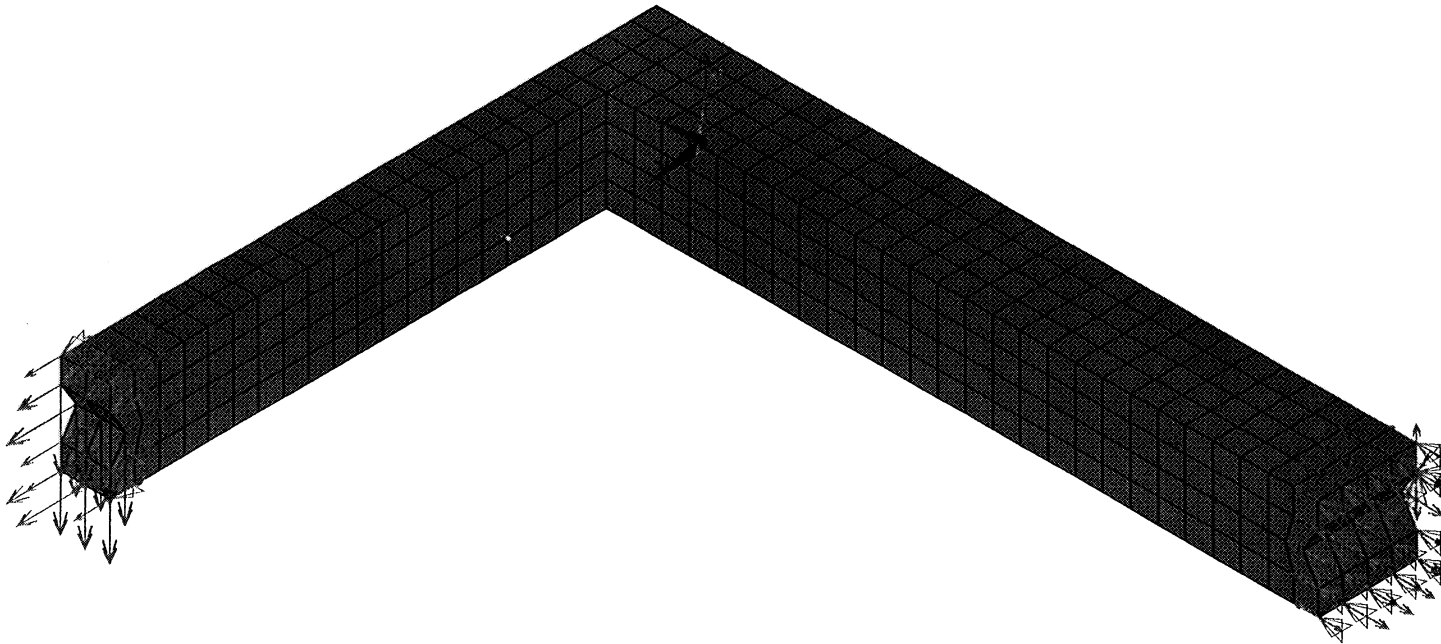
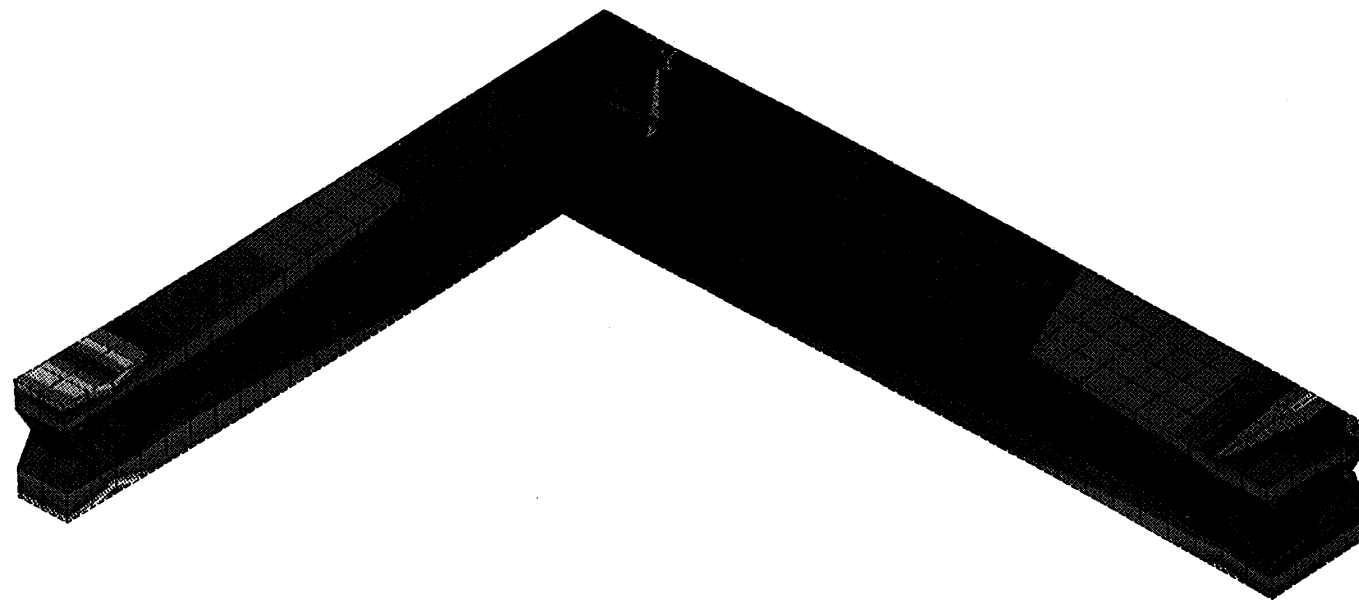


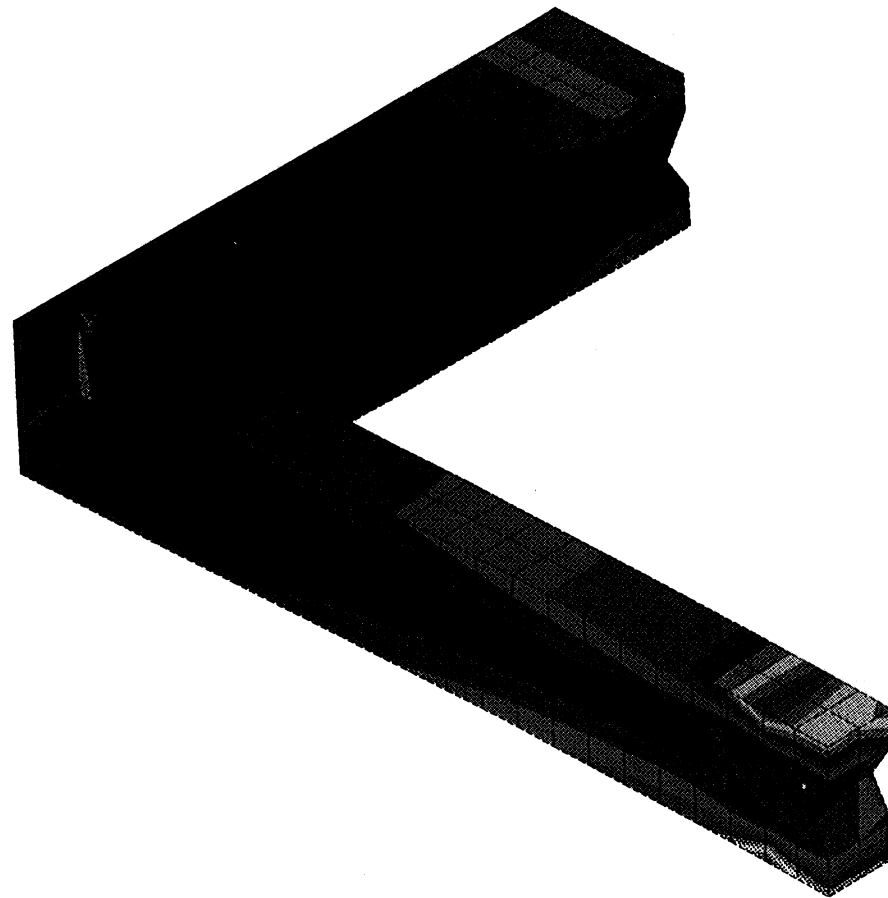
Figure 6: Load boundary conditions on gimbal





ANSYS 5.1  
MAY 27 1995  
21:26:27  
PLOT NO. 1  
NODAL SOLUTION  
STEP=1  
SUB =1  
TIME=1  
SEQV (AVG)  
DMX =0.280E-03  
SMN =214992  
SMX =0.101E+09  
SMXB=0.118E+09  
214992  
0.114E+08  
0.226E+08  
0.338E+08  
0.450E+08  
0.562E+08  
0.674E+08  
0.786E+08  
0.898E+08  
0.101E+09

Figure 7: Gimbal outer  
arm stress analysis



Inner gyro arm

ANSYS 5.1  
MAY 27 1995  
22:04:31  
PLOT NO. 1  
NODAL SOLUTION  
STEP=1  
SUB =1  
TIME=1  
SEQV (AVG)  
DMX =0.804E-04  
SMN =266629  
SMX =0.479E+08  
SMXB=0.604E+08  
266629  
0.556E+07  
0.109E+08  
0.161E+08  
0.214E+08  
0.267E+08  
0.320E+08  
0.373E+08  
0.426E+08  
0.479E+08

Figure 8: Inner gimbal  
arm stress analysis

# Data Acquisition

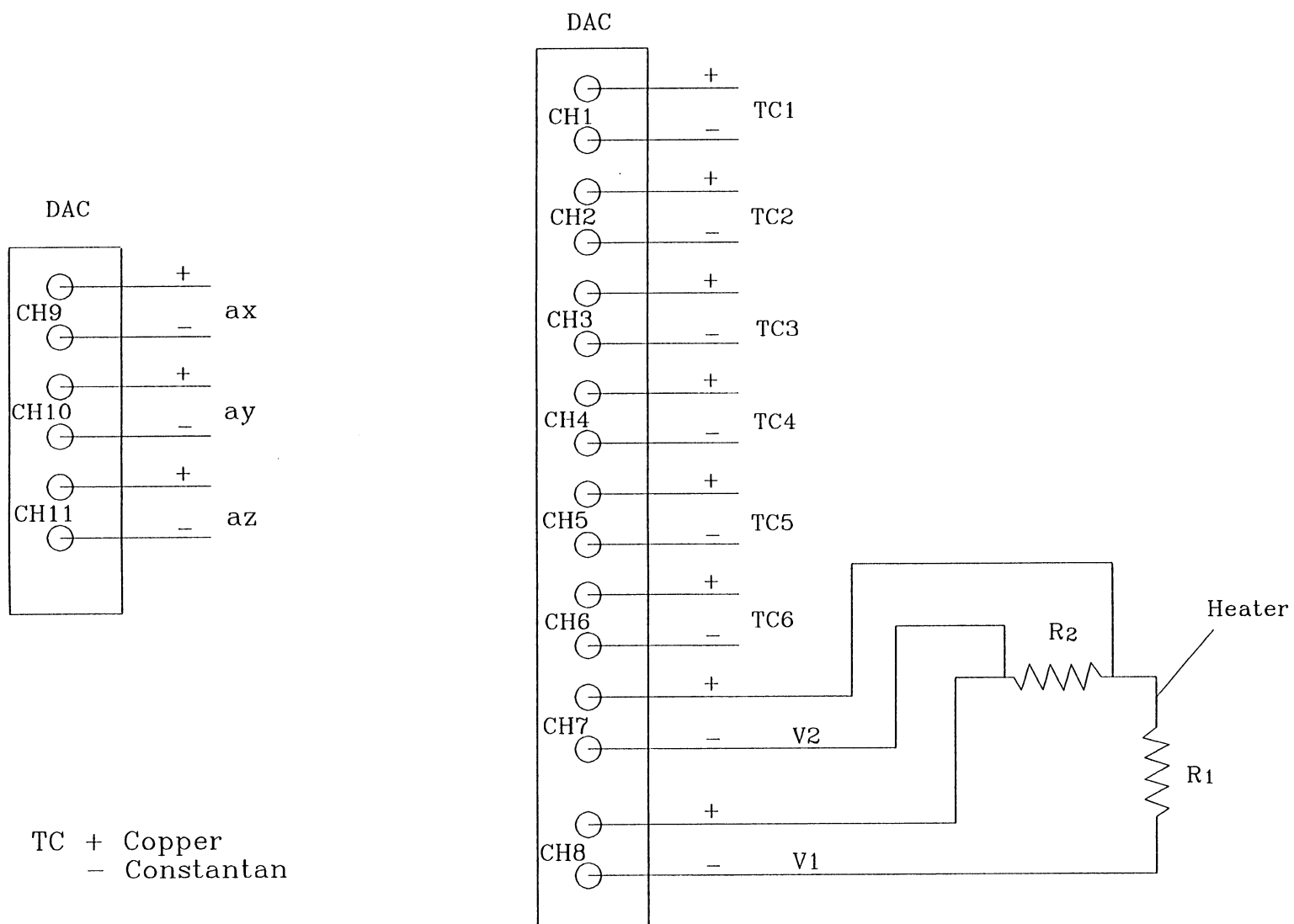


Figure 9: Data acquisition wiring

UK		
DAC		
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SCALE:	DATE	DRAWING NO.

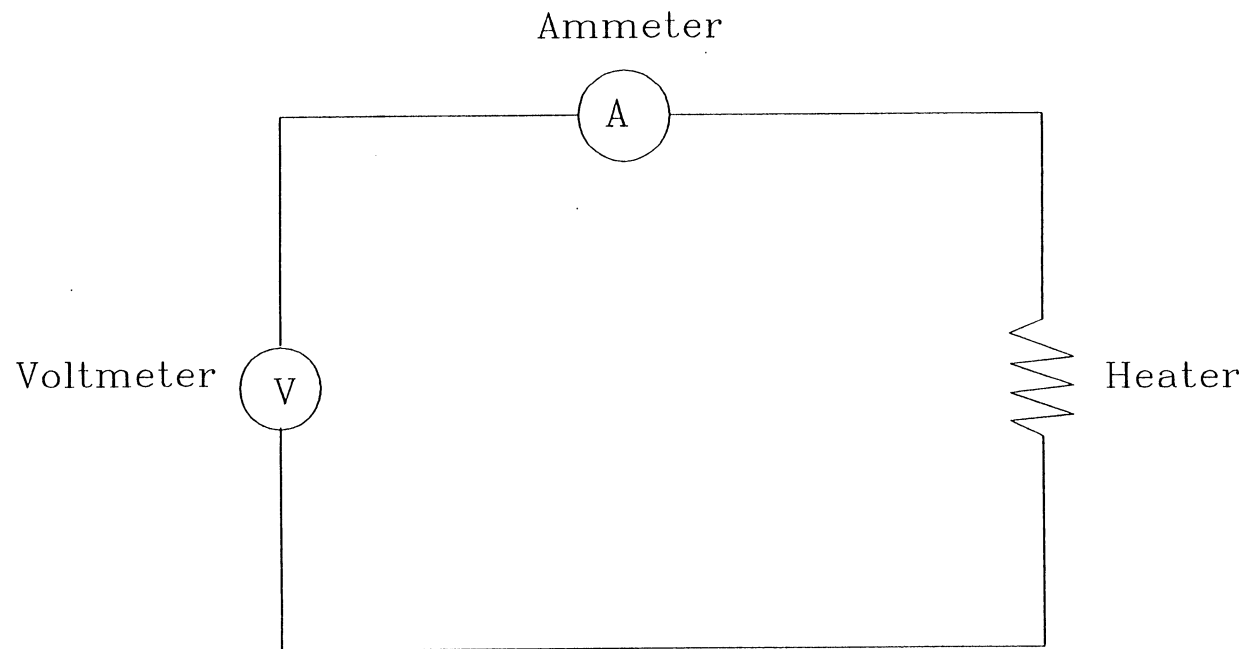


Figure 10: Heater circuit

UK		
CIRCUITS		
1:1	12-Dec-95	
SCALE:	DATE	DRAWING NO.

Appd: A  $T_s = \frac{3566.68}{22.3329 - \ln(P_v)}$  Kelvin  
01-79  
1362  
N/m<sup>2</sup>

3M General Offices  
3M Center  
St. Paul, Minnesota 55144-1000  
612/733-1110  
Duns No.: 00-617-3082

MATERIAL SAFETY  
DATA SHEET

3M

DIVISION: INDUSTRIAL CHEMICAL PRODUCTS DIVISION  
TRADE NAME:

FC-72 FLUORINERT Brand Electronic Liquid  
3M I.D. NUMBER: 98-0211-0216-9 98-0211-0217-7 98-0211-0267-2 98-0211-1795-1  
98-0211-4860-0

ISSUED: APRIL 12, 1989  
SUPERSEDES: JULY 22, 1988  
DOCUMENT: 10-3789-4

$$\sigma = 0.042705 \left( 1 - \frac{T_w}{T_c} \right)^{1.2532}$$

1. INGREDIENT	C.A.S. NO.	PERCENT	EXPOSURE VALUE UNIT	LIMITS TYPE AUTH
Perfluoro compounds, C5-18	86508-42-1	100.0	NONE NONE	NONE NONE

SOURCE OF EXPOSURE LIMIT DATA:  
- NONE: None Established

2. PHYSICAL DATA

BOILING POINT:..... 56.00 C  
(Typical)  
VAPOR PRESSURE:..... ca. 232.0000 mmHg  
Calc. @ R.T.  
VAPOR DENSITY: ..... ca. 11.70 Air = 1  
Calc. @ R.T.  
EVAPORATION RATE:..... > 1.00 Butyl Acetate = 1  
SOLUBILITY IN WATER: ..... nil  
SP. GRAVITY:..... ca. 1.700 Water = 1  
PERCENT VOLATILE: ..... ca. 100.00 %  
VOLATILE ORGANICS: ..... N/D  
pH: ..... N/A  
VISCOSITY: ..... ca. 0.4 centistokes  
@ R.T.  
APPEARANCE AND ODOR: Colorless, clear, odorless liquid.

3. FIRE AND EXPLOSION HAZARD DATA

FLASH POINT:..... None (Setaflash CC)  
FLAMMABLE LIMITS - LEL: ..... N/A  
FLAMMABLE LIMITS - UEL: ..... N/A  
AUTOIGNITION TEMPERATURE: ... N/D  
EXTINGUISHING MEDIA:  
Not Flammable  
SPECIAL FIRE FIGHTING PROCEDURES:  
Not Applicable  
UNUSUAL FIRE AND EXPLOSION HAZARDS:  
Toxic by-products may form upon decomposition (See Section 4).

4. REACTIVITY DATA

STABILITY: Stable  
INCOMPATIBILITY - MATERIALS TO AVOID:  
Finely divided active metals, alkali and alkaline earth metals.  
HAZARDOUS POLYMERIZATION: Will Not Occur  
HAZARDOUS DECOMPOSITION PRODUCTS:  
Thermal decomposition may produce trace amounts of HF and in some cases PFIB. Trace decomposition at 200 C and increased decomposition with increased surface temperatures.

Abbreviations: N/D - Not Determined N/A - Not Applicable

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**MATERIAL SAFETY  
DATA SHEET**

**3M**

**MSDS: FC-72 FLUORINERT Brand Electronic Liquid  
APRIL 12, 1989**

**PAGE: 2 of 3**

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**5. ENVIRONMENTAL INFORMATION**

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**SPILL RESPONSE:**

Observe precautions from other sections. Cover with inorganic absorbent material. Collect spilled material. Place in a closed container.

**RECOMMENDED DISPOSAL:**

Evaporate small quantities, <1 gal., in a hood. To reclaim or return, contact your 3M sales representative. U.S. EPA Hazardous Waste No.: None (Not U.S. EPA Hazardous)

**ENVIRONMENTAL DATA:**

COD= Nil; BOD20= Nil; 96-Hr. LC50, Fathead Minnow(Pimephales promelas)= >1000 mg/l (of immiscible mixture); U.S. Clean Water Act, Section 307, Toxic Pollutants = None.

**SARA HAZARD CLASS:**

**FIRE HAZARD: No PRESSURE: No REACTIVITY: No ACUTE: Yes CHRONIC: No**

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**6. SUGGESTED FIRST AID**

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**EYE CONTACT:**

Flush with plenty of water. Call a physician.

**SKIN CONTACT:**

Wash affected area with soap and water.

**INHALATION:**

If exposed to decomposition products, remove person to fresh air. Call a physician.

**IF SWALLOWED:**

Call a physician or Poison Control Center with detailed description. Include possible material that contaminated liquid during use.

**OTHER FIRST AID:**

NONE

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**7. PRECAUTIONARY INFORMATION**

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FC-72 is not expected to present a hazard when used with good industrial hygiene practices under the following conditions. Use only in areas with sufficient local exhaust ventilation to maintain airborne concentrations at recognized health and safety levels. Avoid prolonged breathing of vapors. Do not breathe thermal decomposition products. Avoid eye contact; wear safety glasses. Do not smoke when using the product. Local exhaust ventilation with a minimum capture velocity of 50 linear feet per minute should be provided for applications at or above the boiling point. If interfering air currents are present, minimum capture velocity should be at least 100 linear feet per minute.

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01-79  
1364

MATERIAL SAFETY  
DATA SHEET



MSDS: FC-72 FLUORINERT Brand Electronic Liquid  
APRIL 12, 1989

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7. PRECAUTIONARY INFORMATION (continued)

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**SPECIAL PROTECTION:**

EYE PROTECTION: Safety Glasses

SKIN PROTECTION: None required at room temperature.

VENTILATION: Local exhaust recommended for temperatures. > or at boiling point.

RESPIRATORY PROTECTION: If decomposition occurs, in the absence of adequate ventilation, an air supplied respirator should be worn.

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8. HEALTH HAZARD DATA

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EYE CONTACT: FC-72 is not expected to produce significant irritation of the eyes on contact. After FC-72 has been in use, contaminants may be introduced that may cause irritation of the eyes.

SKIN CONTACT: FC-72 is not expected to cause irritation of the skin after limited, direct contact. After FC-72 has been in use, contaminants may be introduced that may cause irritation to the skin.

INHALATION: The hazards associated with vapors of FC-72 are expected to be low. Above the boiling point small amounts of toxic decomposition products which may include hydrogen fluoride (HF) and perfluoroisobutylene (PFIB) may occur. Hydrogen fluoride (HF) has an ACGIH threshold limit value of 3 ppm of fluoride as a ceiling limit and an OSHA PEL of 3 ppm of fluoride as an eight hour time-weighted average and 6 ppm of fluoride as a Short Term Exposure Limit. Perfluoroisobutylene (PFIB) has a 3M recommended exposure guideline of 0.01 parts per million parts of air as a ceiling value.

INGESTION: FC-72 is expected to be practically non-toxic by ingestion. After FC-72 has been in use, contaminants may be introduced that are toxic by ingestion.

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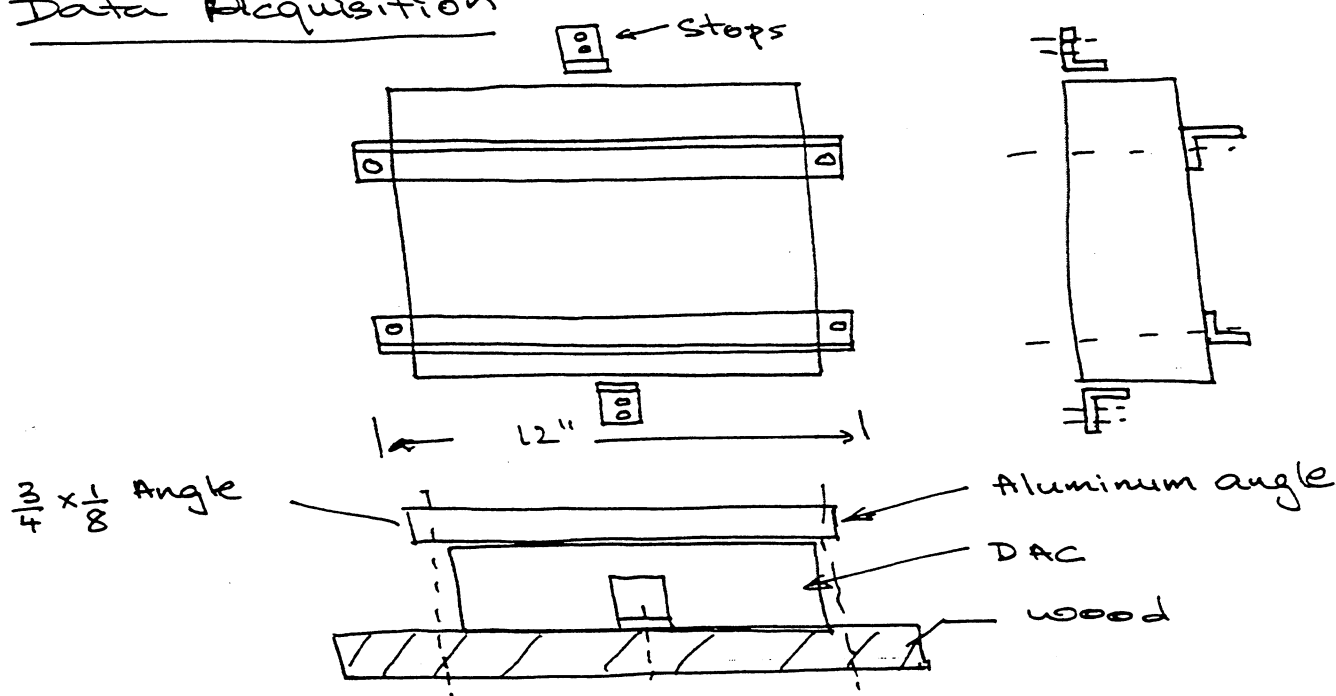
Abbreviations: N/D - Not Determined N/A - Not Applicable

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The information on this Data Sheet represents our current data and best opinion as to the proper use in handling of this product under normal conditions. Any use of the product which is not in conformance with this Data Sheet or which involves using the product in combination with any other product or any other process is the responsibility of the user.

## Appendix B

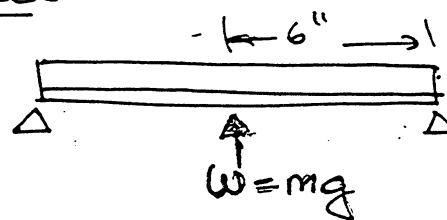
### Data Acquisition



The data acquisition is held down by clamps made up of a set of two  $\frac{3}{4} \times \frac{1}{8}$  Aluminum angles bolted down by  $\frac{3}{16}$  screws to the wooden base.

#### Analysis on AL. Angle brace

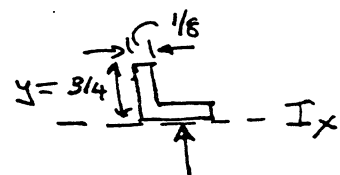
- The maximum stress induced in the angle is if the total weight of the DAC was



imposed as a point load at  $\bar{y}$ 's.

$$\text{Then } \sigma = - \frac{MY}{I_x}$$

$$\sigma_{\text{angle}} = \frac{(mg \cdot 6'') \times \frac{3}{4}''}{A\bar{y}^2 + \frac{1}{3} [t(c-\bar{y})^3 + a\bar{y}^3 - b(\bar{y}-t)^3]}$$



$$t = \frac{1}{8} \quad A = t(a+d)$$

$$c = \frac{3}{4}$$

$$\bar{y} = \frac{c^2 + bt}{2(a+d)}$$

$$a = \frac{3}{4}$$

$$b = \frac{5}{18} = d$$



mass of DAC = 8 lbs.

$$\bar{y} = \frac{c^2 + bt}{2(a+d)} = \frac{3/4^2 + 5/8 \times 1/8}{2(3/4 + 5/8)} = 0.233$$

$$g = 7 \times 32.2 \quad ; \quad A = 1/8 (3/4 + 5/8) = 0.172$$

$$\sigma = \frac{8 \times 7 \times 6 \times 3/4}{0.172 \times 0.233^2 + \frac{1}{3} \times \frac{4}{8} \left[ \frac{(3/4 - 0.233)^3}{8} + \frac{3}{4} (0.233)^3 - \frac{5}{8} (0.233 - \frac{1}{8})^3 \right]}$$

$$= 14003 \text{ lb/in}^2$$

Since there are two angles, this load is split

$$\sigma_{\max} = \underline{7002} \ll \sigma_{\text{YAL}} = 40,000$$

↑ stress in angle AL.

Stress in bolts in angle AL.

The screws holding down the DAC are four 3/16 steel bolts in the angle brace.

$$\sigma_{\max} = \frac{F}{A} = \frac{8 \times 7}{\frac{\pi (3/16)^2 \times 4}{4}} = \underline{507} \text{ lb/in}^2$$

$$\sigma_{\max} \ll \sigma_{\text{Yield steel}} = 48,000 \text{ lb/in}^2$$

stress in stops

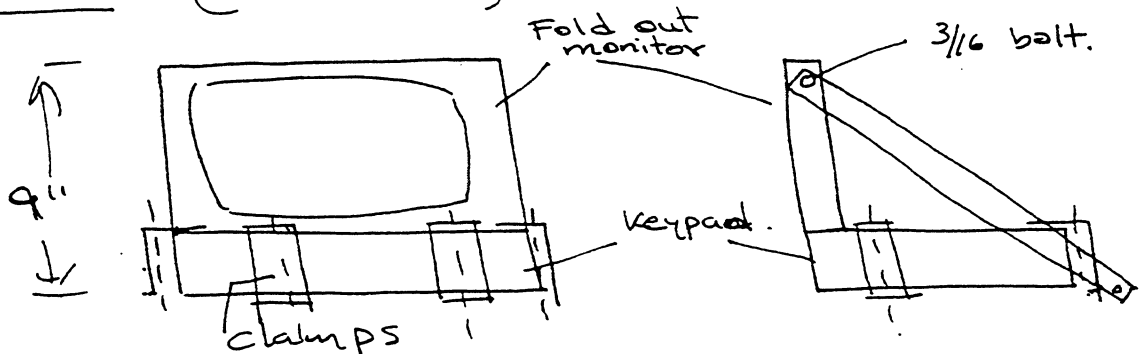
Two bolts hold each stop. If the DAC were to slide out of the brace horizontally then the stops would hold them in position. Hence.

shear stress in stops-bolt

$$\tau_s = \frac{8 \times 7 \times 4}{2 \times \pi (3/16)^2} = \underline{1014} \text{ lb/in}^2$$

$$\ll \sigma_{\text{Yield steel}} = 48,000 \text{ lb/in}^2$$

Computer ( $m = 14 \text{ lbs}$ )



The pc-notebook computer is clamped to the baseplate using angle aluminum clamps. The fold out screen is held rigid in the open position using an angle aluminum brace. ~~also~~

Analysis

Brace on screen

Screen mass = 3 lbs.

$$mg \times 4.5 = R \times 9$$

$$R = \frac{3 \times 7 \times 4.5}{9} = 10.5$$

$$\text{shear on bolt} = \frac{10.5 \times 4}{\pi (3/16)^2} = 380 \text{ lb/in}^2$$

$$\tau \ll \text{Yield}_{AL} = 40,000 \text{ lb/in}^2$$

Clamps

Four clamps are used. The maximum load would be  $mg$ . Shear on nuts

$$\tau = \frac{mg}{\# \times \text{Area}} = \frac{14 \times 7 \times 4}{4 \times \pi (3/16)^2} = 887.3 \text{ lb/in}^2$$

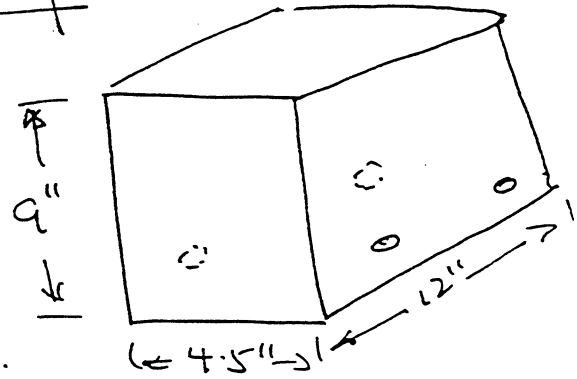
$$\tau \ll \text{Yield}_{AL} = 40,000 \text{ lb/in}^2$$

## Appendix C

Power supply

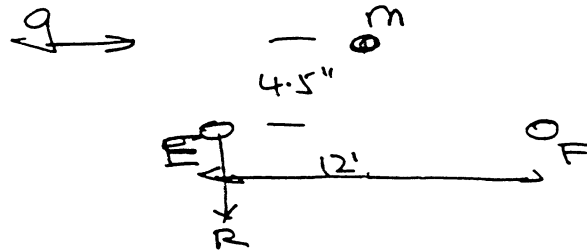
mass = 15 lbs.

The power supply is bolted directly to the frame using  $3/16"$  bolts.



### Maximum Force

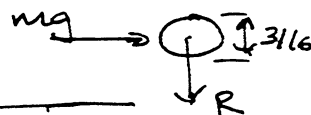
Assuming a horizontal acting 'g', then the bolts will not only support the weight, but also a moment. Taking moments about F



$$mg \times 4.5" = 2 \times R \times 12" \rightarrow (2 \text{ bolts support } R)$$

$$R = \frac{gm \times 4.5}{24} = \frac{15 \times 7 \times 4.5}{24} = 19.7 \text{ lbs.}$$

load on each bolt



$$\text{Resultant force} = \sqrt{mg^2 + R^2} = \sqrt{(15 \times 7)^2 + (19.7)^2}$$

$$\hat{F} = 106.9.$$

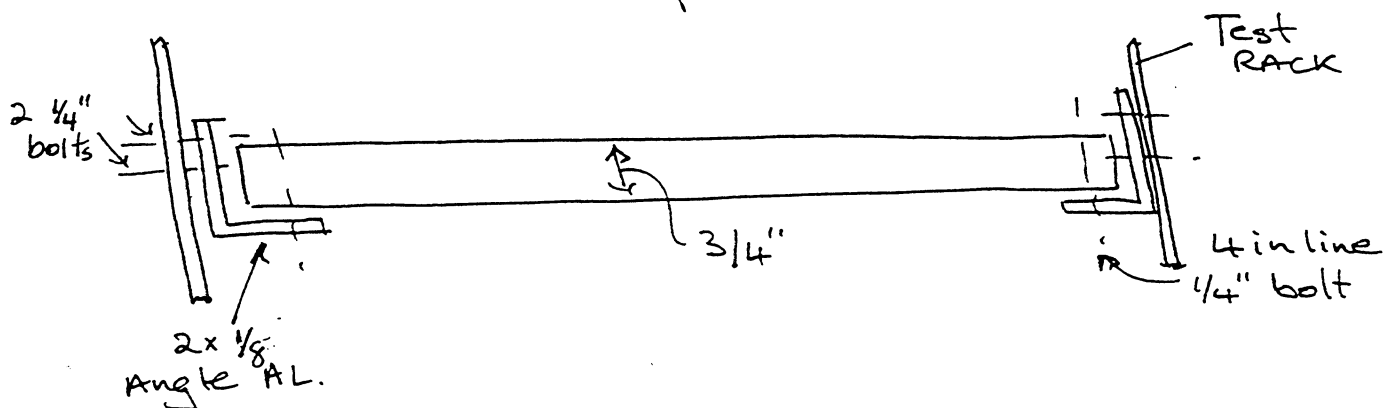
shear stress

$$\tau_s = \frac{\hat{F}}{A} = \frac{106.9 \times 4}{\pi (3/16)^2} = \underline{\underline{3869 \text{ lb/in}^2}}$$

$$\tau_s \ll \text{yield}_{\text{steel}} = 48000 \text{ lb/in}^2$$

# WOODEN SHELF

## Appendix D



The shelf is of real oak wood.  $3/4$ " thick. It is supported by two  $2 \times 1/8$ " angle aluminum on each side using 4  $1/4$ " bolts (steel) on each side. The total load on the bolts is:

$$Mg = (M_{PC} + M_{DAC} + M_{PWR SUPPLY} + M_{WOOD})g$$

$$M_{WOOD} = (3/4" \times 19" \times 20 \ 3/4") 0.66 \times 0.036 = 7 \text{ lbs}$$

$$M_{PS} = 14$$

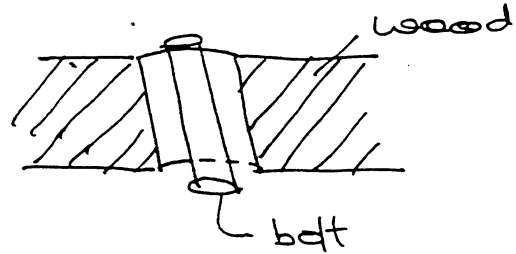
$$M_{PWR SUPPLY} = 15$$

$$M_{DAC} = 8$$

$$\therefore \text{Shear stress in bolts} = \frac{(7 + 14 + 15 + 8) \times 7 \times 4}{8 \times \pi (1/4)^2}$$

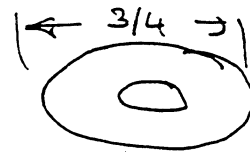
$$\tau_{bolt} = \frac{784}{\pi} \text{ lb/in}^2 < 48,000 \text{ lb/in}^2$$

The load is transferred from the bolts to the wooden shelf. A cross-section through a bolt hole is shown. The stress in the shelf can be a compressive stress in the plane of the wood, in which case:



$$\begin{aligned}\sigma_{\text{wood max}} &= \frac{Wg}{8 (\text{hole surface area})} \\ &= \frac{(7 + 14 + 15 + 8) \times 7}{8 \times \pi \times (1/4) \times 3/4} \\ &= \underline{65} \text{ lb/in}^2 \\ &< < \text{stress parallel to grain} = 800 \frac{\text{lb}}{\text{in}^2}\end{aligned}$$

The bolt is clamped on to the wooden shelf using a 3/4 diameter washer as shown, to spread the load in the direction perpendicular to the plane of the shelf. Hence the compressive stress perpendicular to the grain is:



$$\begin{aligned}\sigma_{\text{comp}} &= \frac{Wg}{8 \times \text{washer area}} \\ &= \frac{44 \times 7 \times 4}{8 \times \pi (3/4)^2} = \underline{87} \text{ lb/in}^2 \\ &< < \text{Yield wood perpendicular to grain} = 1010 \text{ lb/in}^2\end{aligned}$$